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A COMPARISON OF THE STATIC AND FATIGUE STRENGTHS OF FORMED AND DRILLED HOLES IN COMPOSITE LAMINATES

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Holes in structural members introduce areas of high stress concentration. When "laying-up" a laminate composite, it is possible to form the holes before cure, instead of cutting the fibers by drilling the holes after cure. The diverted fibers maintain their continuity and provide added strength in the highly stressed region around the hole. Accordingly, it was hypothesized that a laminate with formed holes would be stronger than a similar laminate with drilled holes.

A series of tests were carried out on graphite epoxy laminates to

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investigate the validity of the above idea. An 18-ply $(0^\circ/\pm45^\circ2/0^\circ{}_2/\pm45^\circ)_S$ lay-up was chosen for the test specimens. Holes of 6.35 mm dia. (1/4 in.) were formed in the B-stage GR/EP laminate by diverting the fibers and inserting steel pins to form the holes. The pins were removed after the cure cycle. Tension, compression, shearout and bearing specimens were prepared and tested, along with similar samples with drilled holes.

Results of open hole tests on formed hole specimens showed a 50% improvement in tensile strength and a 26% improvement in compressive strength over drilled hole specimens. The shearout specimens of both types failed at essentially the same loads. Finally, the formed hole bearing specimens experienced an initial yielding at approximately 50% of the ultimate bearing load, whereas the drilled hole specimens yielded at 75% of ultimate. However, the ultimate load in bearing for both types of specimen was about the same.

In addition, a series of open hole fatigue tests were conducted to compare fatigue characteristics (R = 0) & (R = -1) of a GR/EP laminate containing a formed hole to one containing a drilled hole. Test results showed excellent fatigue properties for the formed hole specimens and established that their added static strength capability could be fully utilized in structural component design.

S U M M A R Y

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INTRODUCTION

Stress concentrations around holes in structural members are very often the locations where failures originate, particularly in structures under severe fatigue loading. Furthermore, since mechanical attachments - rivets, screws, bolts, etc. - are still the primary means of making joints, holes are almost unavoidable in aircraft structures. The designer, therefore, must continually deal with the stress concentrations around holes and the resulting reduction in structural strength.

For metal structures this problem is usually alleviated by locally increasing the material thickness, introducing favorable local residual stresses by cold working, etc. In composite materials these techniques are either not applicable or difficult to use, and other concepts must be found for reducing the penalty due to local stress concentrations.

In this report the results of an investigation on a new concept for making holes in composite materials are presented. The salient feature of this concept is that the holes are formed by diverting the fibers in the laminated prepreg without cutting them, rather than by drilling after the prepreg is cured. There are two advantages associated with this hole forming procedure: more continuous fibers orientated along the load path in the highly loaded regions, and diverting of load away from the boundary of the hole.

The logical result of doing this is that the gross design stress level for a structural element can be increased, thus reducing structural weight and increasing structural efficiency.

FABRICATION OF FORMED HOLES

Figures 1a and 1b show the comparison between a drilled hole and a formed hole. It is shown schematically that fibers have been rerouted rather than cut for the formed hole in a typical 0°, $\pm 45^\circ$ laminate. Figure 2 illustrates the fiber paths around the hole in the different plies.

Forming the hole is basically a four step process, as shown in Figure 3. For this study, 18 ply graphite epoxy laminates were used for the fabrication investigation and for the tests which were performed. The panel is layed-up, then vacuum bagged and precompacted under 585 k Pa (85 psig) to insure integral contact of all the individual plies. The first step in Figure 3 shows the entire lay-up, including the GR/EP panel itself, layers of bleeder cloth and other necessary bagging materials, a top 16 mm (1/16 in.) thick aluminum pressure plate and a bottom guide plate, each identically drilled with 6.35 mm (1/4 in.) dia. holes spaced according to the desired hole spacing. The top aluminum plate is used as a template to locate the formed holes. Heat, approximately $65^\circ C$ is applied locally to the site of each hole before forming, to soften the epoxy matrix and prevent breaking of the graphite fibers by the forming process. Holes are actually formed by pressing a tapered tool down through the entire B-stage layup, gradually spreading the graphite

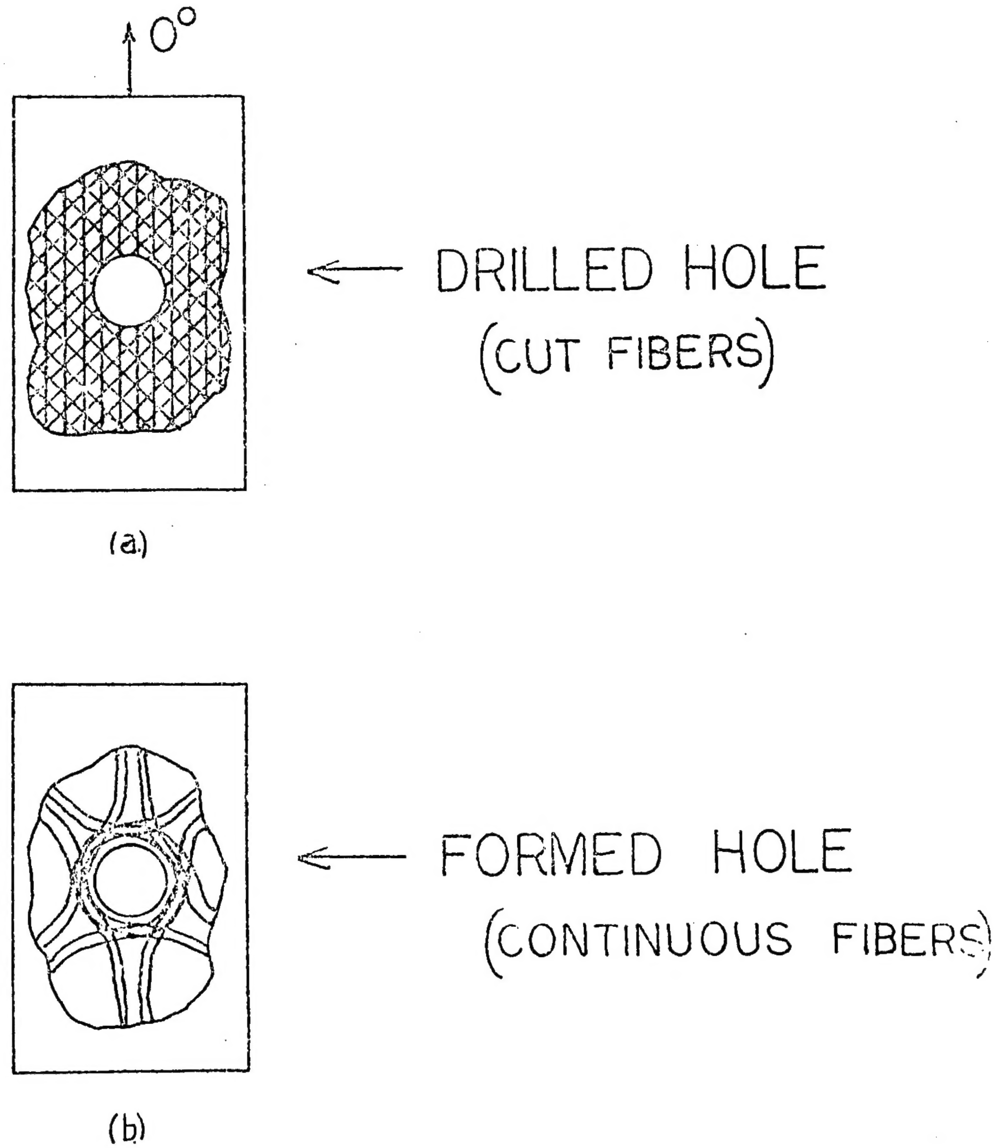


Figure 1. Concept of Formed Holes in a GR/EP Laminate

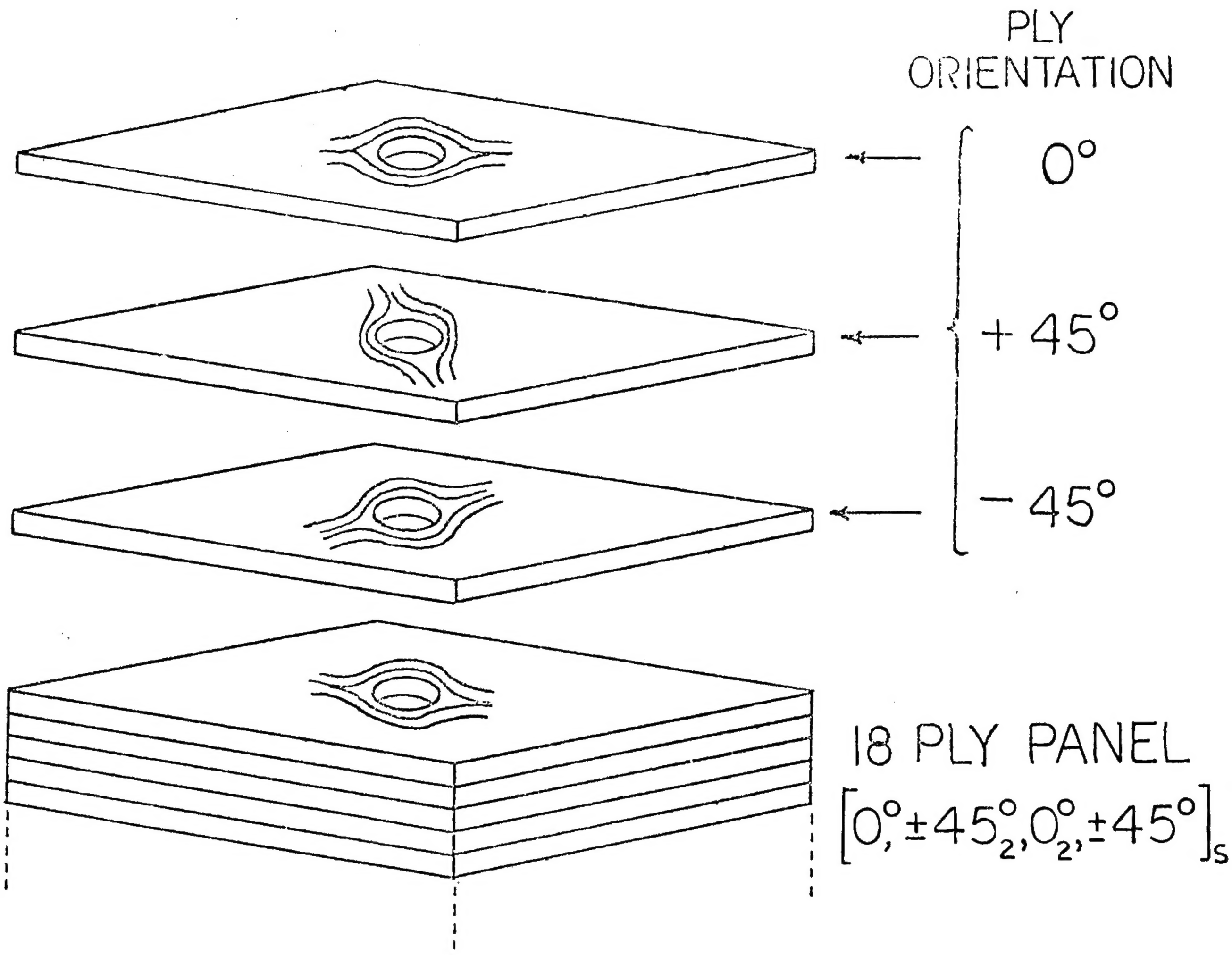


Figure 2. Fiber Spreading to Form Hole

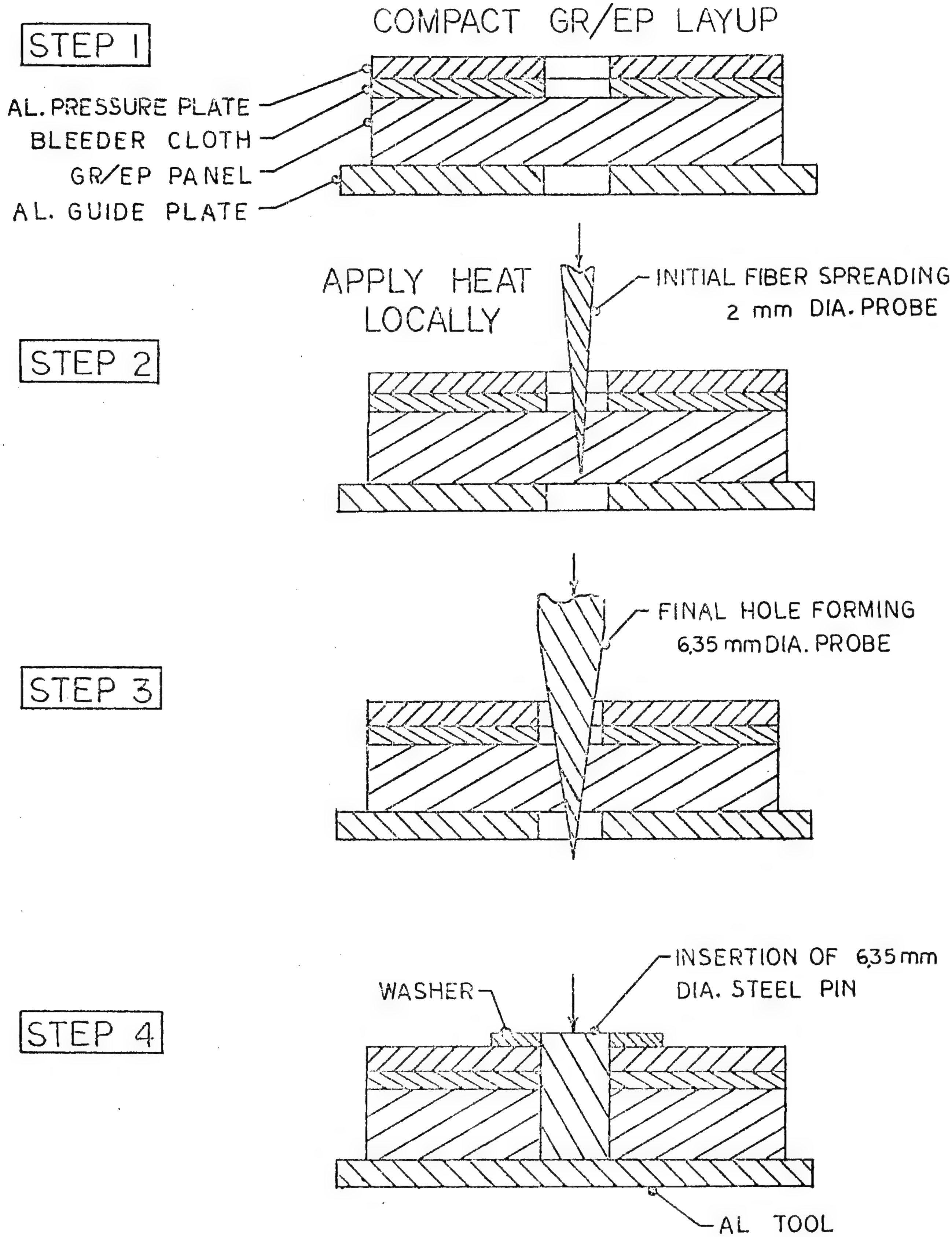


Figure 3. Fabrication Process

to the desired hole diameter, 6.35 mm (1/4 in.) in this case, (steps 2 and 3). After each hole is formed a 6.35 mm (1/4 in.) diameter steel pin is inserted to maintain the hole shape during the cure cycle, step 4 (also see Figure 4). After cure the pins are driven out, leaving the finished formed holes, (Figure 5). Note that the protective peel ply layer is still attached to the surface GR/EP ply, causing the formed holes shown in Figure 5 to lack clear definition.

It should be pointed out that there is an approximate 10% increase in laminate thickness in the immediate area around the formed holes.

For production, tens or even hundreds of holes could be formed in one stroke with little recurrent manufacturing cost. Therefore, although this procedure seems cumbersome on a laboratory scale, it is considered to be a practical manufacturing process with potential cost savings.

STATIC TESTING

Testing was conducted to establish the static capabilities of a GR/EP laminate containing a formed hole, as compared with one containing a drilled hole. Tension, compression, bearing, and shearout specimens were fabricated in accordance with the specimen configurations pictured in Figure 6. All specimens were cut from 18 ply panels with $(0^\circ/\pm45^\circ{}_2/0^\circ{}_2/\pm45^\circ)_S$ orientation. Several batches of specimens were fabricated utilizing the following prepregs - Narmco 5208 and 5209, and Hercules 3501/AS. For all batches, drilled hole specimens and baseline specimens with no holes were made and tested for comparison to the formed hole results.

TENSION TEST RESULTS

Table I lists the results of the static tension tests. Three different prepreg systems were used, and the results of each are tabulated separately. All specimens were tested to failure on an Instron test machine.

Three types of tension specimens were tested, baseline samples without any hole, specimens with a centered 6.35 mm (1/4 in.) diameter drilled hole and similar specimens with 6.35 mm (1/4 in.) diameter formed holes. The number of each type of specimen tested, the average ultimate load, and the average nominal ultimate stress are listed. Comparison between the drilled and formed hole samples is made by calculating a nominal stress concentration factor for each. This index of comparison was obtained by dividing the average nominal ultimate stress of each of the open hole specimen groups into the average ultimate stress of the baseline specimens.

It is seen that in all cases the nominal stress concentration for the formed holes is substantially less than for the drilled holes. Results were consistent for all prepreg groups, with improvement in formed hole static strengths ranging from 35% for the Narmco 5208 to 59% for the

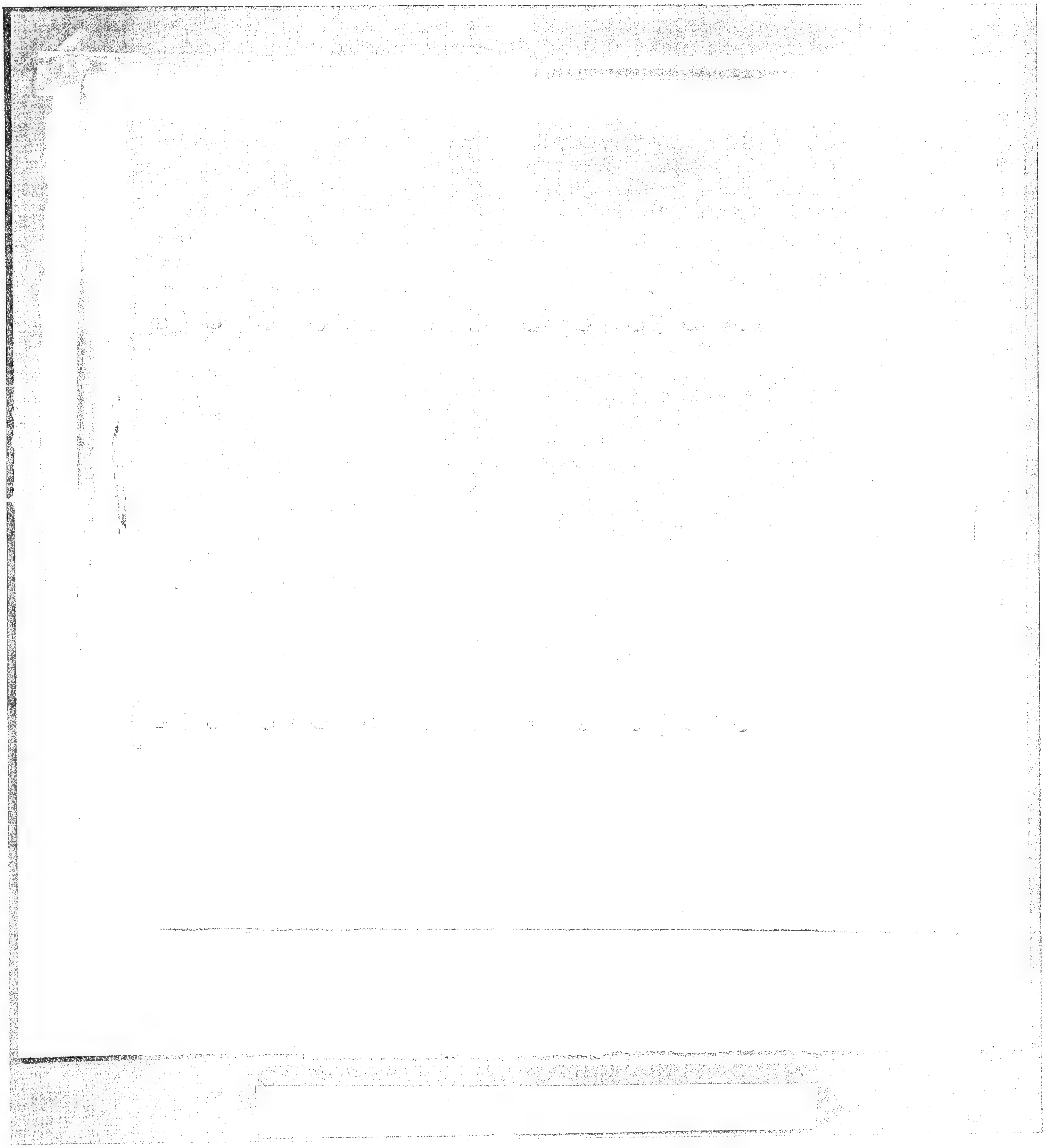


Figure 4. Layup Assembly - GR/EP Formed Hole Panel

Figure 5. [illegible] Panel

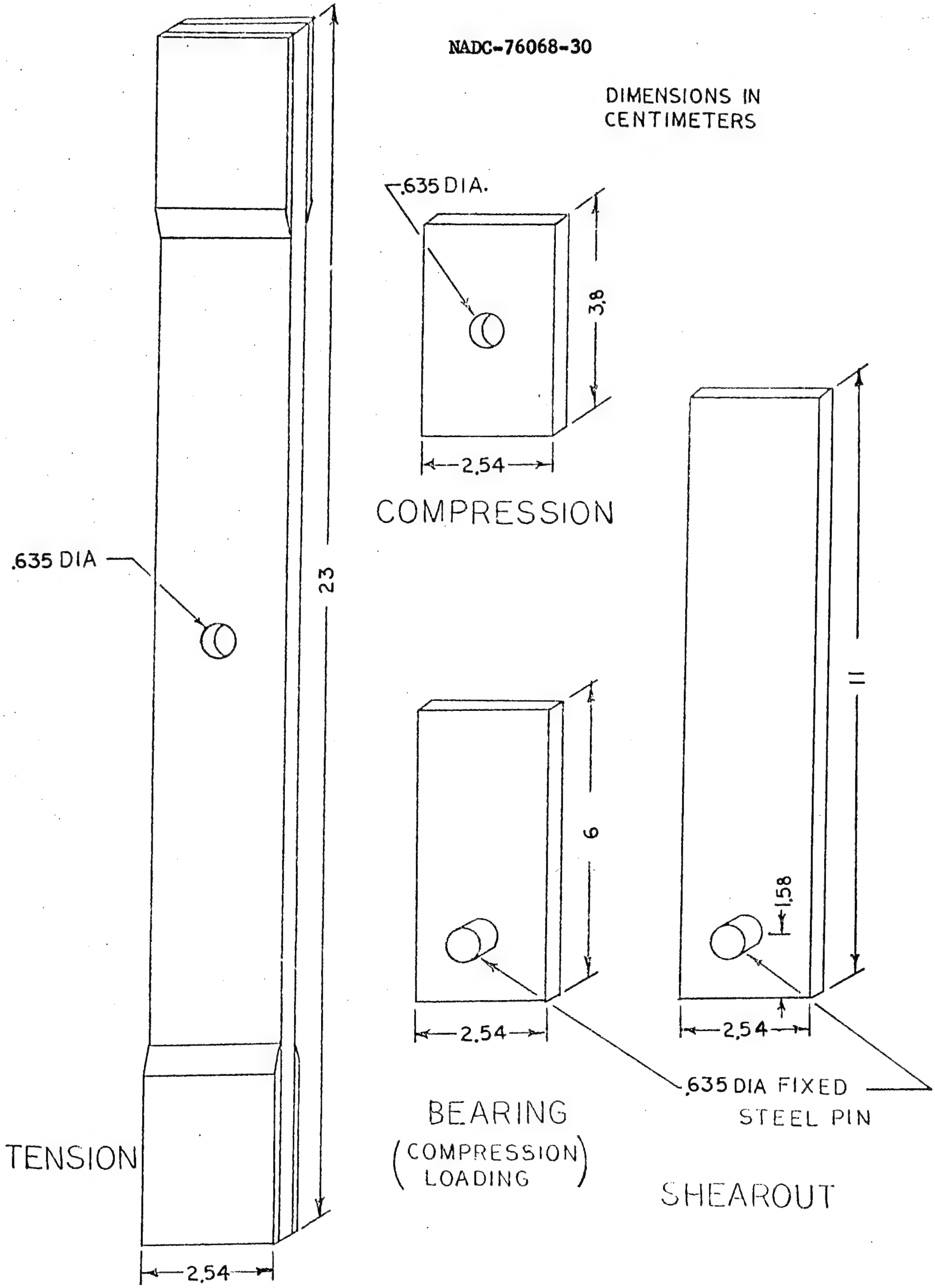


Figure 6. Specimen Configurations

TYPE SPECIMEN	NO TESTED	AVE ULT LOAD P_{ULT} (N)	AVE STRESS $\sigma_u = \frac{P_{ULT}}{wt}$ (M Pa)	NOMINAL STRESS CONC. FAC. "K"
BASE (NO HOLE)	5	35630	410.9	1.00
DRILLED HOLE	10	21710	249.6	1.64
FORMED HOLE	8	29580	340.6	1.20

PRE-PREG - NARMCO 5209

BASE	19	33540	496.4	1.00
DRILLED HOLE	13	17700	260.6	1.89
FORMED HOLE	13	28070	413.7	1.19

PRE-PREG - HERCULES 3501/AS

BASE	3	31310	509.5	1.00
DRILLED HOLE	2	19570	317.2	1.60
FORMED HOLE	3	25980	427.5	1.21

PRE-PREG - NARMCO 5208

Table I. Results - Static Tension

Hercules 3501/AS. Considering all the data together in Table II, the reduction in nominal stress was from 1.85 to 1.19 or a 50% increase in strength.

Scatter of the test results is illustrated on a simple bar diagram, Figure 7, and for simplicity only the Hercules 3501/AS results are shown. The scatter range of the formed hole data is 2-1/2 times that of the drilled hole data, although the low end of the formed hole bar is still 22% higher than the high end of the drilled hole bar. Similar scatter was noticed in the other two pre-preg groups. It is expected that the scatter would be reduced, if better controlled fabrication procedures were followed.

It is evident from the substantial reduction in the "K" index that utilizing the formed hole in a ($0^\circ/\pm45^\circ$) balanced GR/EP laminate offers superior static strength in tension as compared to the ones with drilled holes.

COMPRESSION TEST RESULTS

Similar results were obtained for specimens in compression as well as in tension. Results are listed in Table III. Only one batch of specimens was tested, (Narmco 5209 pre-preg). Again, comparison of the nominal stress concentration obtained for the formed hole specimens with that for the drilled hole specimens shows a 26% improvement in strength for specimens with formed holes.

BEARING AND SHEAROUT TEST RESULTS

The testing performed up to this point showed significant improvements to be realized by using formed holes. In order to be sure that these gains were not being achieved at the expense of other load carrying capabilities, bearing and shearout tests were conducted. The results of these tests, shown in Tables IV and V, proved that there are no significant differences in ultimate bearing and shearout strength between the two kinds of specimens. Table IV gives the bearing test results. An average yield load and an average ultimate load for each group of specimens is shown. Notice that the formed hole specimens experienced yielding at a lower average load than the drilled samples, 7520 N (1690 lbs.) compared with 10630 N (2390 lbs.), a 29% decrease. However, the average ultimate load in bearing for both types of specimens was about the same. On the surface, the lower yield strength in bearing may appear to be a drawback, but in reality most fastener holes in aircraft are in the low load or medium load transfer category, where bearing is not critical. In addition, yielding permits load redistribution, which is a desirable feature, particularly for composites, which have less ductility than metals.

The shearout specimens of both types failed at approximately the same average load of 13000 N (2900 lbs.) as seen in Table V. An edge distance to diameter ratio of 2-1/2 was used.

TYPE SPECIMEN	NO. TESTED	AVE ULT LOAD P_{ULT} (N)	AVE STRESS $\sigma_u = \frac{P_{ULT}}{wt}$ (MPa)	NOMINAL STRESS CONC FAC "K"
BASE (NO HOLE)	27	33580	481.3	1.00
DRILLED HOLE	25	18010	260.6	1.85
FORMED HOLE	24	28290	389.6	1.19

Table II. Average Results for All Tension Tests

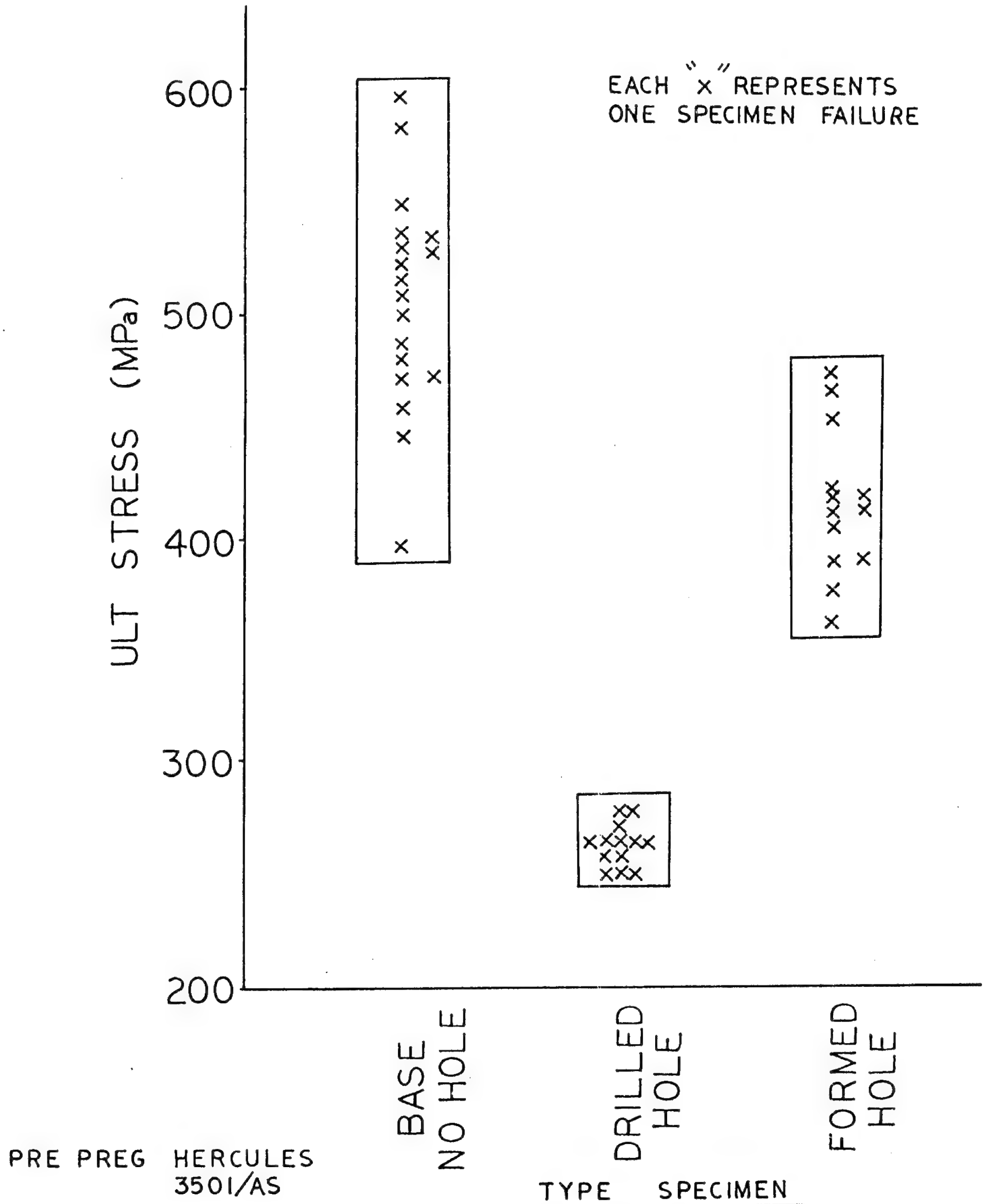


Figure 7. Static Tension Test Data Scatter

TYPE SPECIMEN	NO. TESTED	AVE ULT LOAD P_{ULT} (N)	AVE STRESS $\sigma_u = \frac{P_{ULT}}{wt}$ (MPa)	NOMINAL STRESS CONC. FAC. "K"
BASE (NO HOLE)	5	44480	517.1	1.00
DRILLED HOLE	9	25090	288.9	1.77
FORMED HOLE	10	31360	362.7	1.42

PRE-PREG - NARMCO 5209

Table III. Results - Compression

TYPE SPECIMEN	NO. TESTED	AVE YIELD LOAD (N)	AVE ULT LOAD (N)
DRILLED HOLE	10	10630	13740
FORMED HOLE	10	7520	13790

PRE-PREG -NARMCO 5209

Table IV. Results - Bearing

TYPE SPECIMEN	NO. TESTED	AVE ULT LOAD (N)
DRILLED HOLE	7	12990
FORMED HOLE	8	12940

PRE-PREG - NARMCO 5209

Table V. Results - Shearout

Photographs of formed hole static failures for each type of specimen tested are presented in Figure 8. The tension specimen containing the failure away from the hole was an exception to the typical failure occurring at the hole, but it dramatically demonstrates how the stress concentration around a hole can be reduced by forming the hole.

FATIGUE TESTING

Having established the superiority of formed holes with respect to static strength, the next factor to be considered is that of fatigue endurance. In general, composites are known for their excellent fatigue characteristics, but it was not known at this point whether the formed hole would stand up well under fatigue loading. Therefore, a series of tension-tension (R = 0) fatigue tests was run on both formed and drilled hole specimens. Specimens from the previous NARMCO 5208 and Hercules 3501/AS pre-preg groups had been reserved for these tests.

Specimens were tested on an MTS machine at various peak stress levels, at a frequency of 5 cps. S/N data are plotted in Figure 9. Data points in the upper band represent formed hole specimens, 39 in all, and data points in the lower band represent drilled hole specimens, 5 in all. Four out of five drilled hole data points were run outs, these specimens being cycled to a peak stress in excess of 90% static ultimate, demonstrating that the drilled specimens were very insensitive to fatigue loading.

For the formed hole specimens, strength degrades as a result of the cyclic fatigue loading. However, the high cycle fatigue strength for the formed hole specimens is still higher than the static strength of the drilled hole specimens.

Evaluation of the S/N data is reported here against fatigue requirements for Naval aircraft. Specification MIL-A-8866, shows that the entire gain in static strength by using formed holes instead of drilled holes can be transformed into increases in design allowables. This is because, for the laminate under consideration, the static strength, not the fatigue properties, controls the design allowable. During the course of running the tests, it was observed that a distinct failure mode is associated with formed holes under tensile fatigue loading. Cracks initiate in the matrix and propagate along fibers which run concentric to the hole (see Figure 10). This behavior is typical of the majority of formed hole specimens tested. Cracks appear early in the cycling, stage 1. As cycling continues, more cracks gradually appear, stages 2 and 3, until failure finally occurs, in this case after 500,000 cycles.

Although any type of cracking is undesirable, this type of gradual crack growth is far more desirable than unstable cracking, which initiates without warning. This type of pending failure might be detected early, either visually, or, if heat is generated in this initial cracking, by heat sensing devices.

Typical formed hole fatigue failures are pictured in Figure 11 for several different fatigue lives.

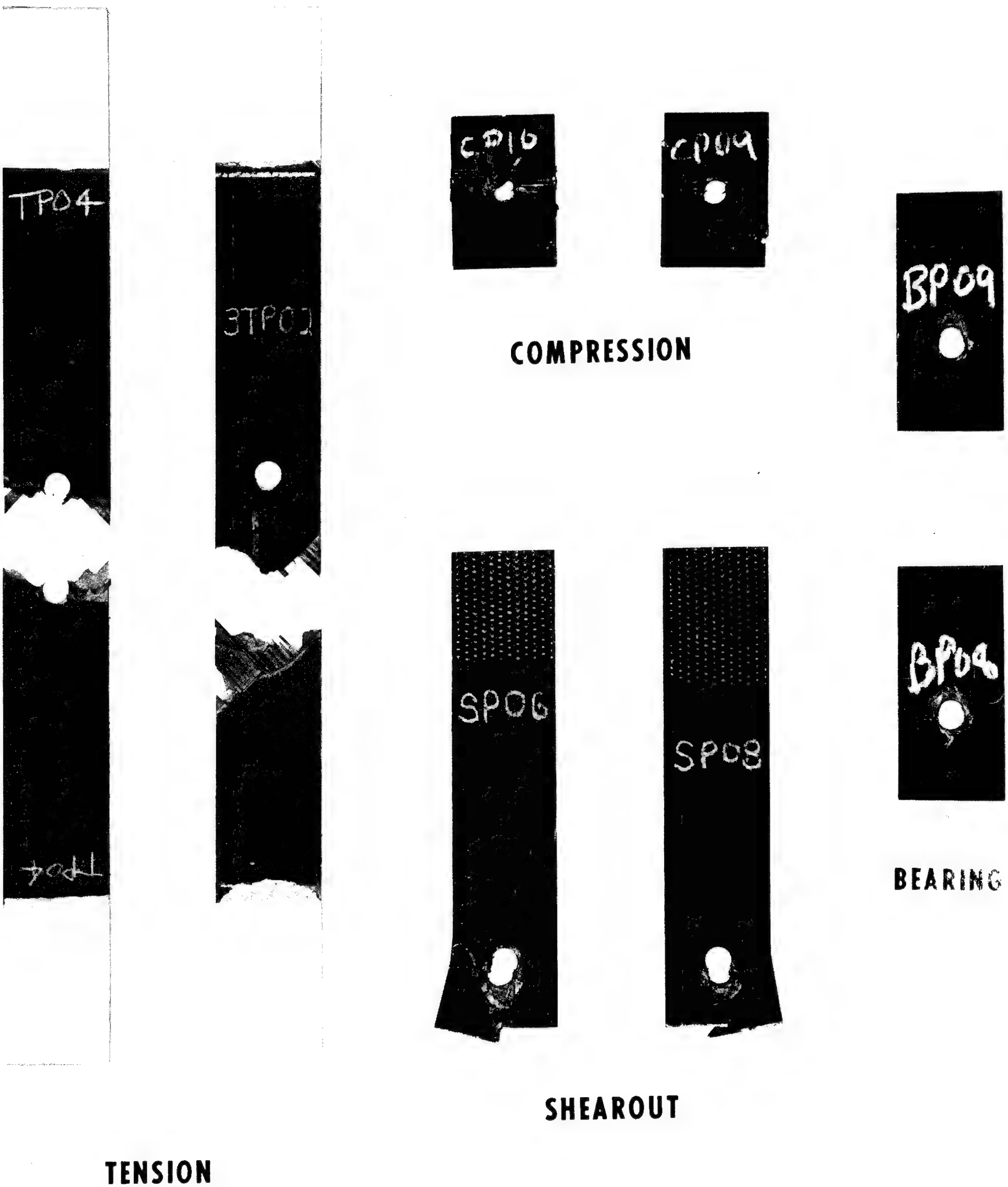


Figure 8. Formed Hole Static Failures

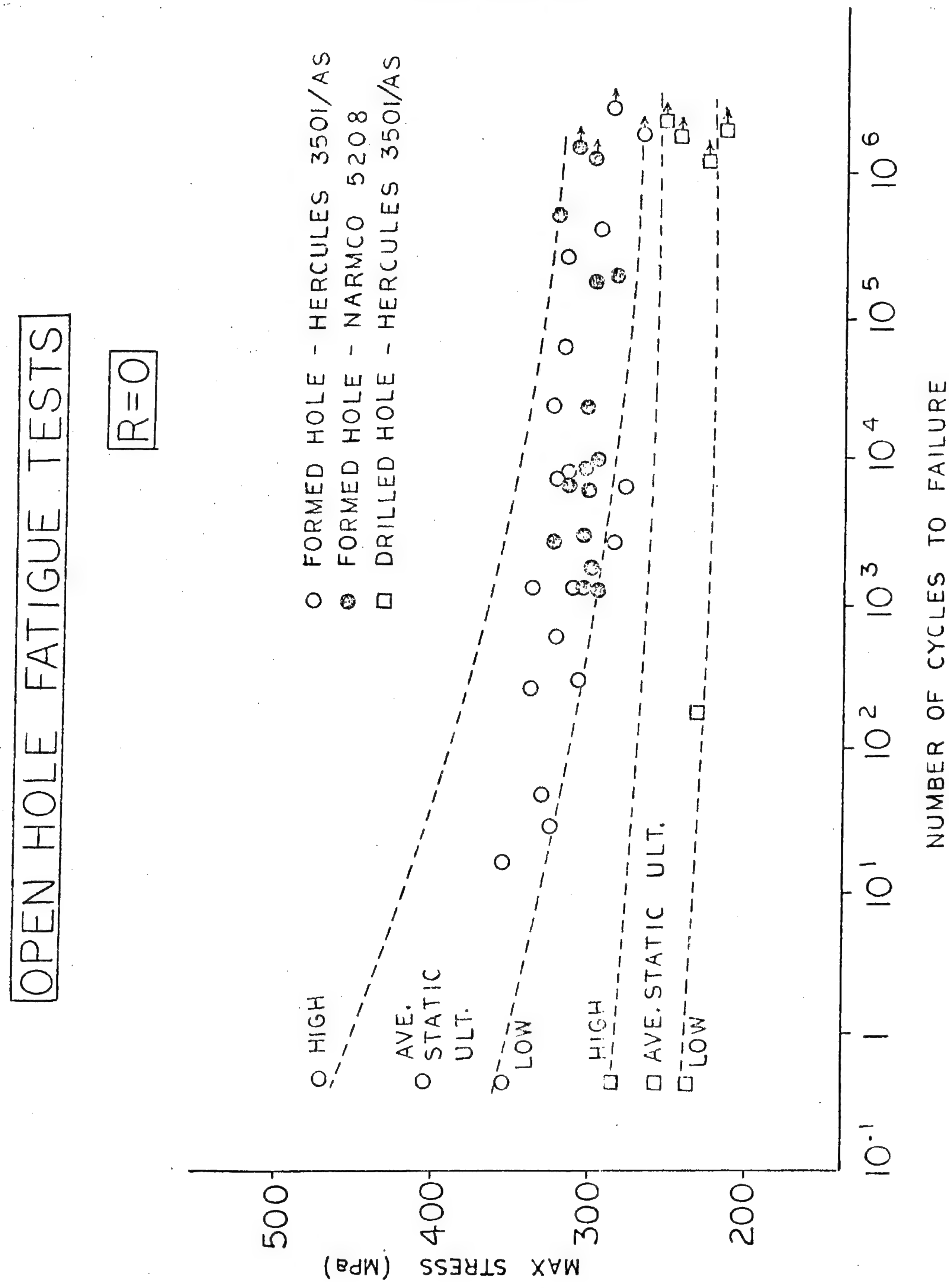


Figure 9. Open Hole Fatigue Tests

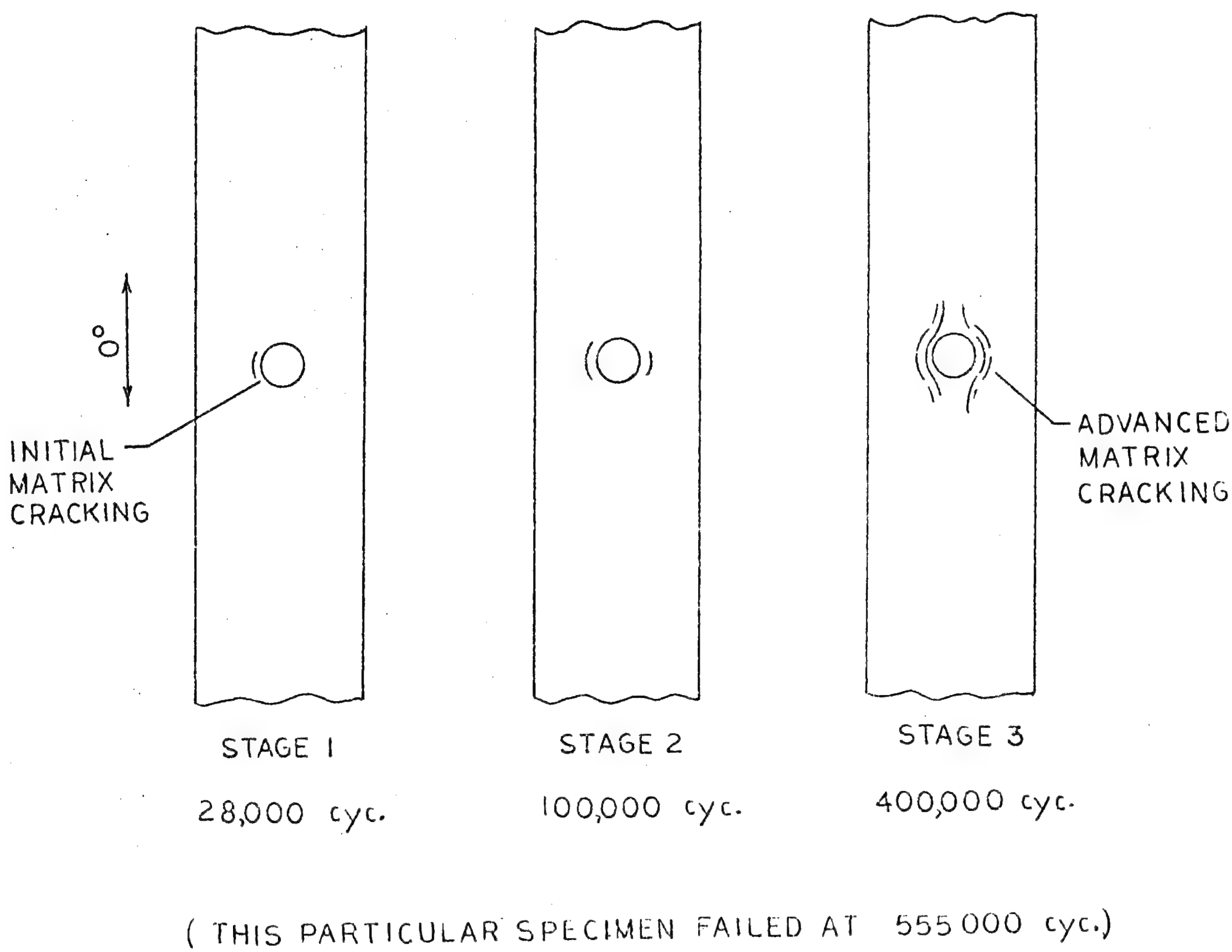
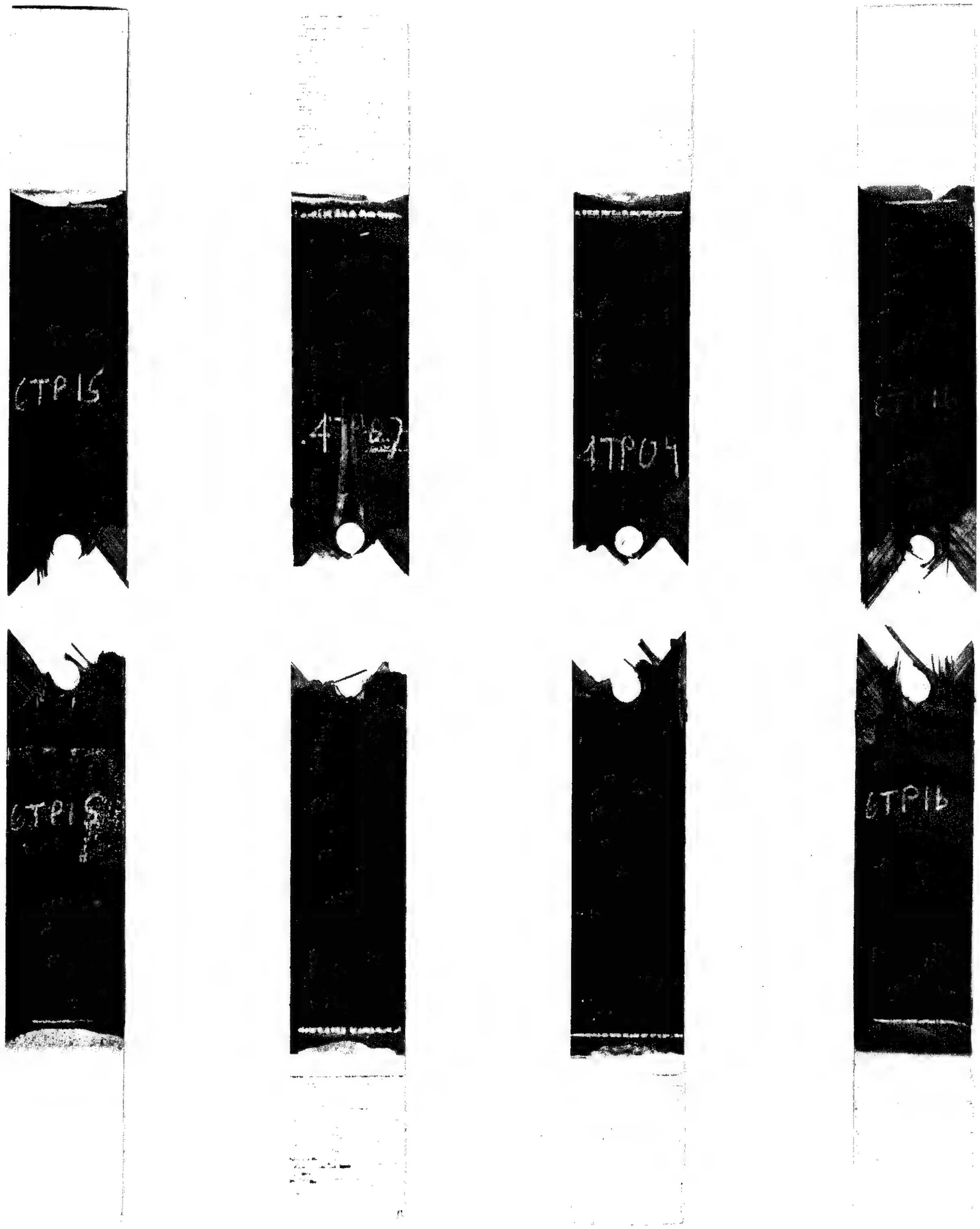


Figure 10. Typical Fatigue Failure Mode - Formed Hole Specimen



2460 cycles	**8990 cycles**	**54,200 cycles**	**555,000 cycles**

Figure 11. Typical Formed Hole Fatigue Failures

FULLY REVERSED FATIGUE LOADING

A small lot of formed hole specimens was fabricated and tested under fully reversed fatigue loading, R=-1. This test condition is considered to be most damaging as far as fatigue is concerned. The configuration of the specimens and the test condition are depicted in Figure 12. Fatigue loading, R=-1, at 5 H_z was applied with peak gross stress level ranging from 40% static compression ultimate to 75% static compression ultimate. Results are shown in Figure 13. It is shown that specimens with formed holes are superior for low cycle fatigue below 100 cycles. For high cycle fatigue the fatigue characteristics for both kinds of specimens are the same. Even though the strength degrades after experiencing a high number of fatigue loadings, the high static strength advantage of the formed hole still can be utilized in the design of Naval aircraft structures.

CONCLUSIONS

The work reported here represents an initial evaluation of the merits of forming holes in composite materials, rather than the usual technique of drilling, which cuts vital load carrying fibers and decreases the strength of the structure. On the basis of the static and fatigue test results, it can be concluded that strength penalties due to stress concentrations will be much less in laminates with formed holes than in ones with drilled holes. Furthermore, because of the inherent superior fatigue properties of advanced composites, the gains in static strength which are achieved with the formed holes can be utilized to the full extent in design and directly translated into weight, cost and/or performance gains.

RECOMMENDATIONS

Further work in this area is recommended and planned in order to more fully evaluate this concept, so that the gains achieved at the laboratory level may be transformed into design practice. This includes the following areas of investigation:

1. An analytical study to quantify the assessed benefits of formed holes.

2. Static and fatigue testing of actual joint configurations, first single attachment lap shear joints and, later, multi-attachment joints.

3. Countersunk holes.

4. Hole size effects.

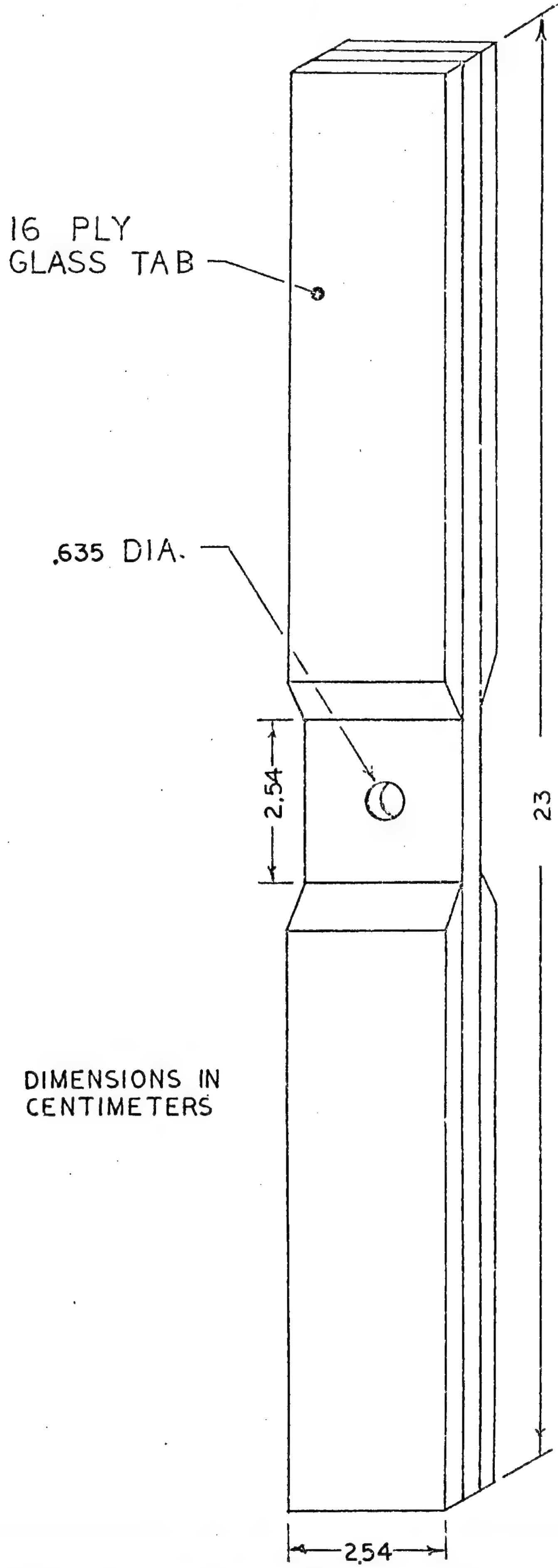


Figure 12. Reverse Loading Specimen

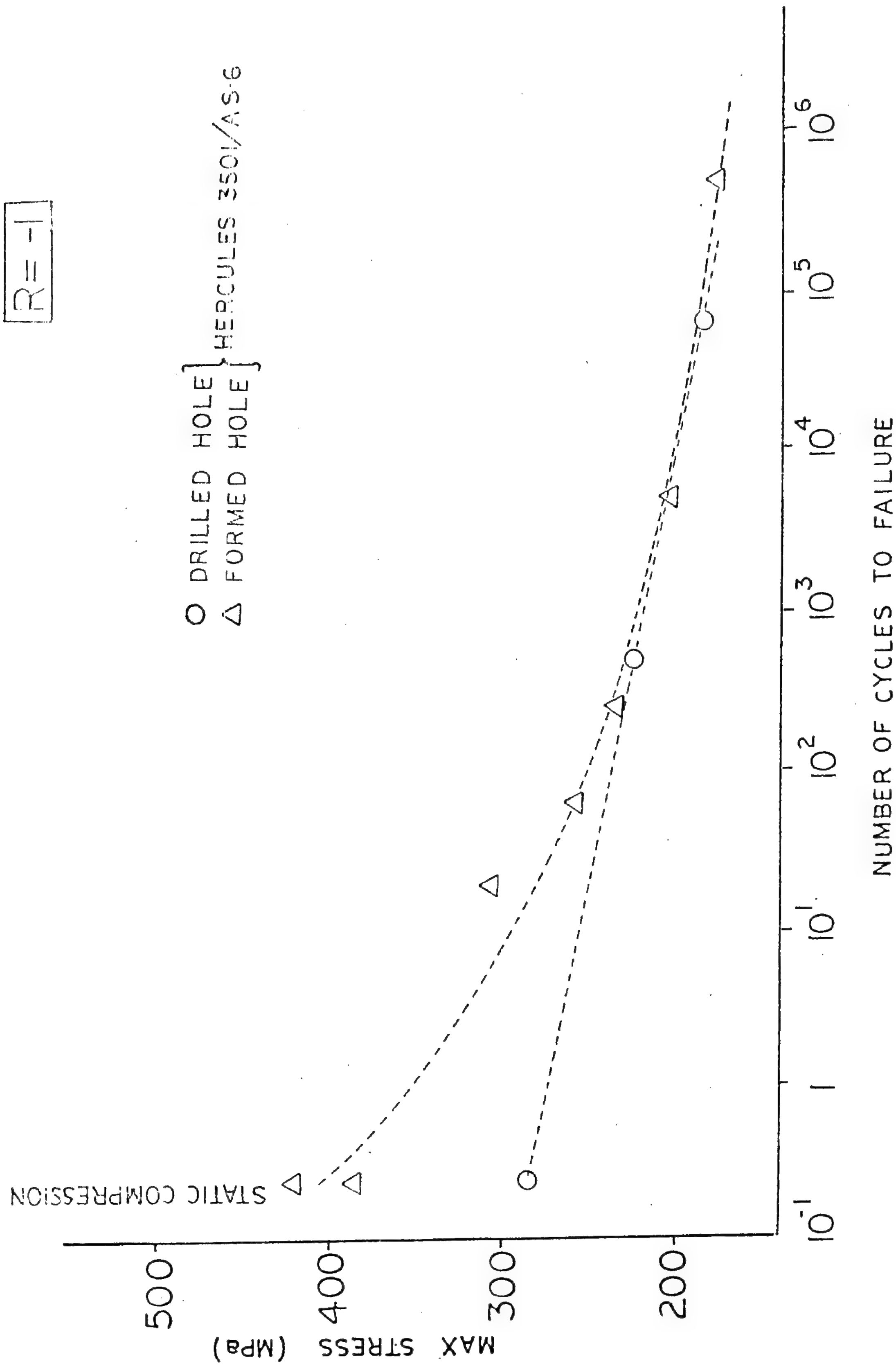


Figure 13. Open Hole Fatigue Tests - Reversed Loading

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